Development of MOEMS and smart systems based on transparent metals

Final Technical Report and invoice

by

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This final interim report includes a statement of the problem studied, a summary of the most important results obtained during the development of the work and in the last four months, after the realization and the chracterization of the designed MOEMS prototypes.
A detailed description of the ethcing procedures techniques at the laboratories of CNM, Spain is reported together with the simulations and the experimental measures made at the laboratories of AMSAM-RD-WS-ST, Huntsville, AL, USA.
A theoretical models of the final transducer is considered thus showing a very high optical sensitivity with respect to the displacement of the realized micro-suspended plates, where the PBG structurs will be deposited in the next future

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Development of MOEMS and smart systems based on transparent metals

Final Interim report

Salvatore Baglio

Abstract

The primary goal of the project was to find some way for integrating PGB structures based on transparent metals and MEMS, to realize a micro device with the same optoelectronic properties proposed by the partners. The strategy has consisted in considering an "air gap" as a layer of a PBG structure between two symmetrical metal-dielectric stacks. The mechanical positioning of the two side of the resulting structure has allowed to control the air gap thickness and then the optical properties of the whole structure. A macro-prototype, based on tubular PZT actuators have been realized for testing the proposed theoretical optical properties.

Then, the problem of realizing MOEMS, that can be adopted both as sensors and actuators, by using technologies compatible with those of standard industrial microelectronics processes has been considered. A standard CMOS process (AMS CMOS 0.8 um) has been adopted, thus allowing straightforward integration of the electronics onto the same substrate of the opto-mechanical device. The conceived micro devices are mainly constituted by a suspended plate that can move vertically against a fixed surface, and both the plate and the fixed surface have been realized with materials transparent to a selected range of wavelengths; the suitable metal-dielectric multilayer film has been deposited onto the two facing surfaces that are therefore separated by the controlled air gap. Mechanical, electromechanical and finite elements models have been developed thus allowing to estimate the static and dynamical behaviour of the proposed devices; therefore, the design of particular heaters, included in the supporting springs of the various devices for realizing thermal actuators, has been addressed. Two different designs have been submitted to the commissioned foundry thus allowing, to acquire a lot of information about the mechanical properties of the materials of this standard microelectronic technology, and about the etching process parameters.

Introduction

This final interim report includes a statement of the problem studied, a summary of the most important results obtained during the development of the work and in the last four months, after the realization and the characterization of the designed MOEMS prototypes.

The problem of realizing MOEMS, that can be adopted both as sensors and actuators, by using standard industrial microelectronics processes has been studied. We started from the theoretical results obtained for PBG structures and "transparent metals" optical properties and their experimental confirmation by a mechanical macro-prototype based on piezoelectric actuators. Then, a standard CMOS process (AMS CMOS 0.8 um) has been considered, thus allowing

straightforward integration of the electronics onto the same substrate of the opto-mechanical device. The developed micro devices are mainly constituted by a suspended plate that can move vertically against a fixed surface, and both the plate and the fixed surface have been realized with materials transparent to a selected range of wavelengths; the suitable metal-dielectric multilayer film is deposited onto the two facing surfaces that are therefore separated by the controlled air gap. Mechanical, electromechanical and finite elements models have been developed thus allowing to estimate the static and dynamical behaviour of the proposed devices; therefore, the design of particular thermal actuators and capacitive or resistive sensors has been addressed. Two different designs have been submitted to the commissioned foundry thus allowing, to acquire a lot of information about the mechanical properties of the materials of this standard microelectronic technology, and about the etching process parameters, whereas a third prototype has to be etched and characterized in the next period.

A detailed description of both the etching procedures and the opto-electro-mechanical characterization of the realized devices, made in the last four moths, is addressed. Several different devices have been correctly released after the TMAH etching phase and some preliminary measures of the roughness of the suspended surfaces have been performed, by using a Wyko surface profilers at the laboratories of Weapons Sciences Directorate, U.S. Army Aviation & Missile Command, AMSAM-RD-WS-ST, Redstone Arsenal, Alabama, USA.

Some different problems, with respect to those encountered with the previous prototypes, have been encountered with the micromachining of the second ICs. In fact, one or two of the oxide layers of the adopted CMOS technology have not been correctly removed from some areas of the IC, thus preventing to uncover the silicon and to release correctly the mechanical structures by the TMAH solution. For the same reason the thermal actuators do not work correctly.

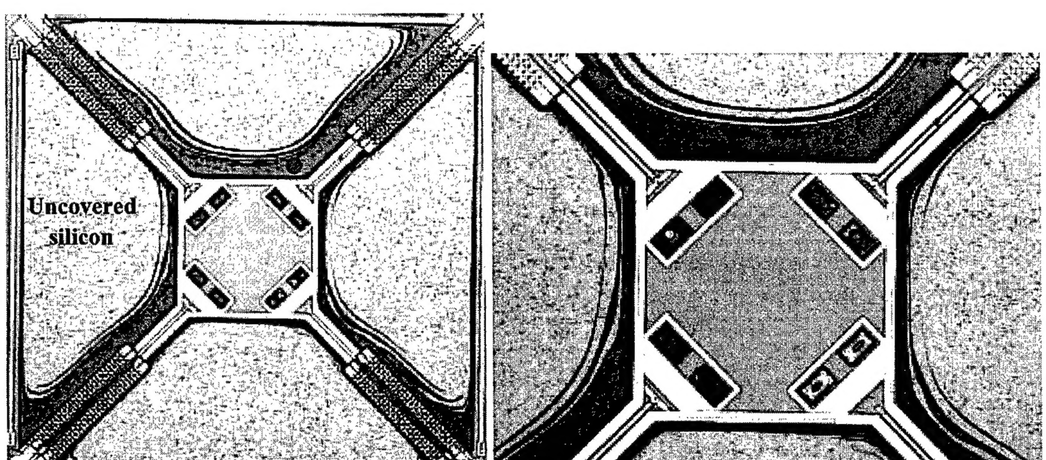
A new run, of the same devices, with some small modifications, have been sent again to the commissioned foundry and the etching procedures of the last prototypes together with their electro-mechanical characterization will be performed in the next period.

Etching procedures at CNM (National Centre of Microelectronic) of Barcelona, Spain...

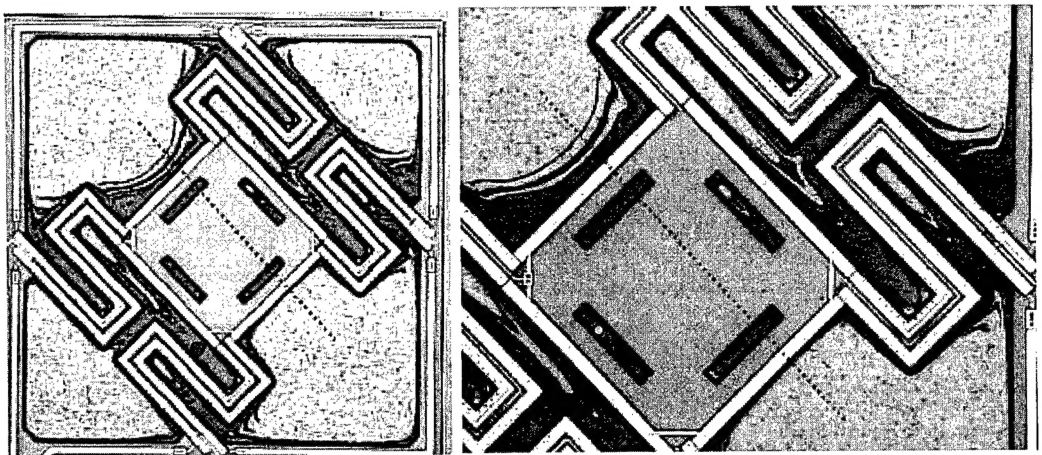
With respect to the previous runs some problems have arisen in the micromachining of the various structures at the laboratories of the commissioned foundry. In particular, as previously stated, some oxides of the adopted technology were not correctly removed, probably to some "shield effect" during the process due to the distance of our dies from the centre of the silicon wafer. In the figures 1-2 this unwanted effect is highlighted by some microscope pictures took at the laboratories

of CNM (National Centre of Microelectronic) in Barcelona, Spain. Two residual oxide layers were not removed (blue-violet regions) and this result has been confirmed by the measures made by using an inteferometric and a mechanical profiler at the laboratories of CNM. A 1.1 ?m thick residual material have been measured in the areas highlighted by the red points, in the figures 1-4, by using an interferometric profiler, and by the red line in the figures 3-4, by using a mechanical profiler. The same residual material has not been removed from the holes realized over the plate, highlighted by the green point in the figures 1-2 and in the figures 3-4. These holes have been conceived to improve the under etch of the large structures. For this reason in a first time a longer etch time has been adopted thus weakening the parts of the structure where the metals were uncovered. Moreover an additional etch step (RIE, reactive ion etching) have been performed, to remove the residual oxide layers, thus weakening, damaging and compromising the structural integrity of some other structures.

By taking into account the structure shown in figures 3-4, the residual oxide hold together the different segment of the designed sustaining springs thus compromising the mechanical functionality of the device. The same effect can be observed for the other devices of the discussed IC, as shown from figure 6 to figure 11.



Figures 1-2 Microscope picture and particular of the device named *Susp_plate_1*. It is mainly made by a suspended plate anchored to the substrate by four straight sustaining arms.



Figures 3-4 Microscope picture and particular of the device named *Susp_plate_2*. It is mainly made by a suspended plate anchored to the substrate by four sustaining arms. The profile of the structure along the red dotted line was measured by using a mechanical profiler thus revealing the thickness of the residual oxide both at one side of the suspended plate and inside the holes of the plate.

While uncovered silicon was expected at the end of the process between the various segments of the designed springs, and inside the holes of the suspended plate, a 1.1 thick residual oxide can be observed in the figure 5.

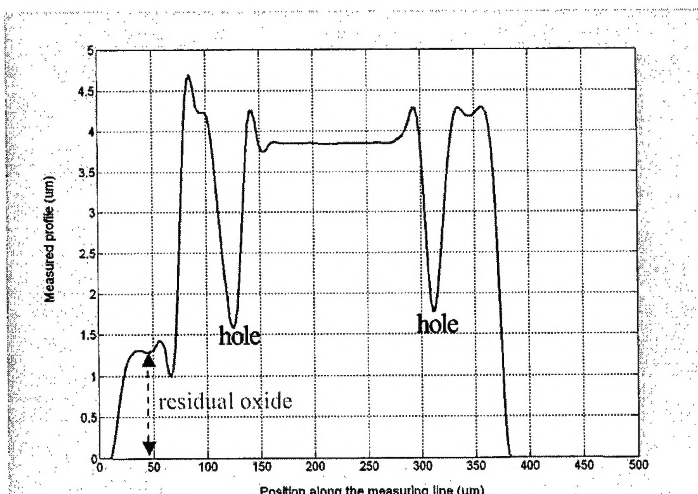
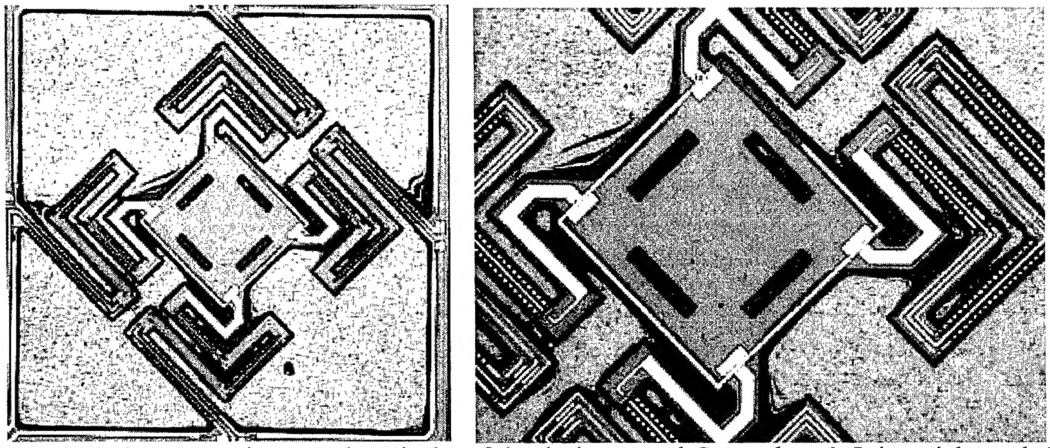
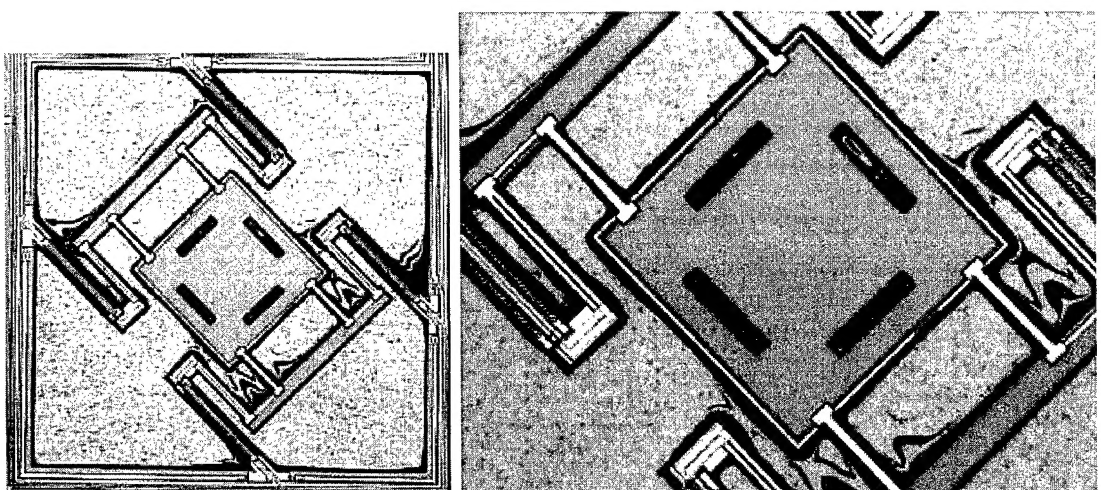


Figure 5 Profile of the structure shown in figures 3-4. A 1.1 thick residual oxide is both present outside the suspended plate and inside the holes of the plate, where uncovered silicon was instead expected.

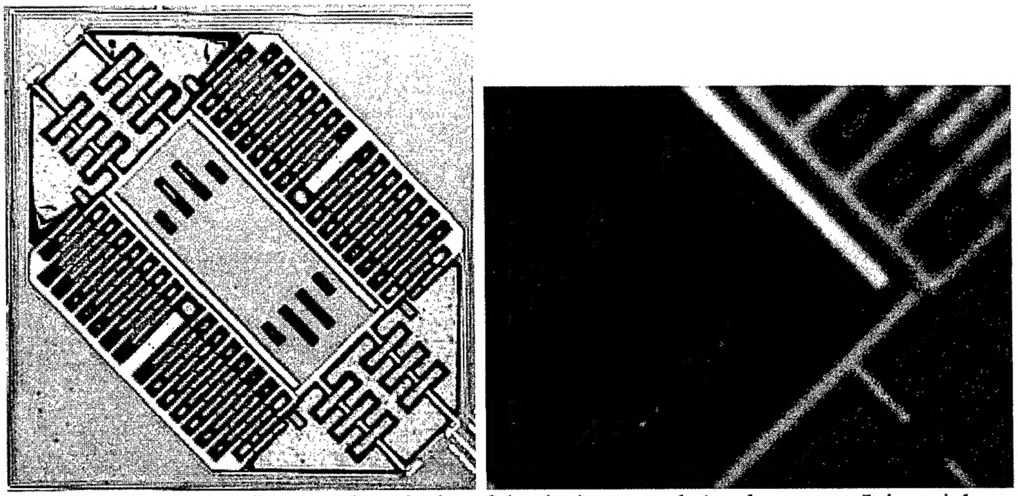
With the adopted RIE (reactive ion etching) the residual oxides were almost completely removed even if a portion of the passivation layer (Si_3N_4), often use a protective layer, was still etched. The adopted plasma has, in fact, an etch rate of about 900 Å/min to the oxides (SiO_2) and an etch rate of about 600 Å/min to the nitrides (Si_3N_4), passivation layer).



Figures 6-7 Microscope picture and particular of the device named *Susp_plate_3*. It is mainly made by a suspended plate anchored to the substrate by four sustaining arms. These longer springs allow to obtain a lower elastic constant and to decrease the mechanical resonance frequency of the structure.

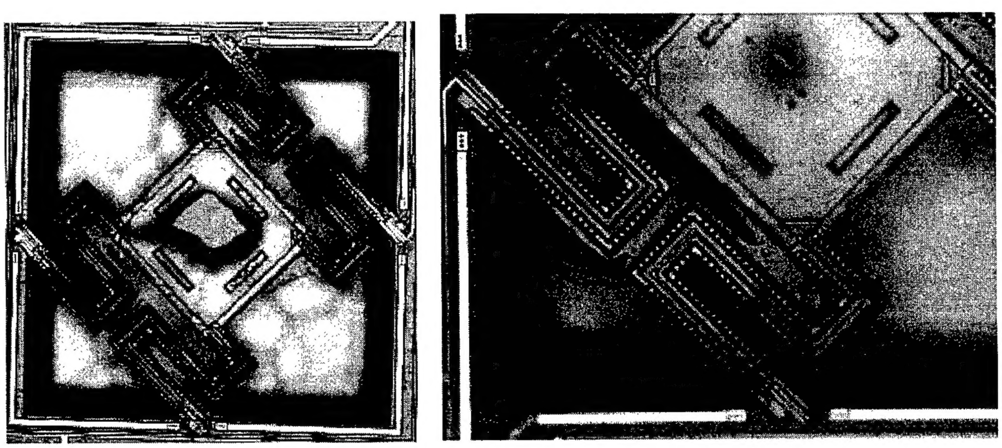


Figures 8-9 Microscope picture and particular of the device named *Susp_plate_4*. It is mainly made by a suspended plate anchored to the substrate by four sustaining arms. In this case a fourth order model represent the mechanical device where a suspended mass is the plate and the other one hold together two springs each side.

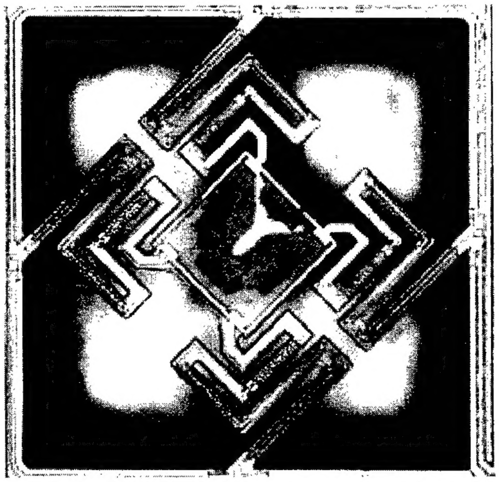
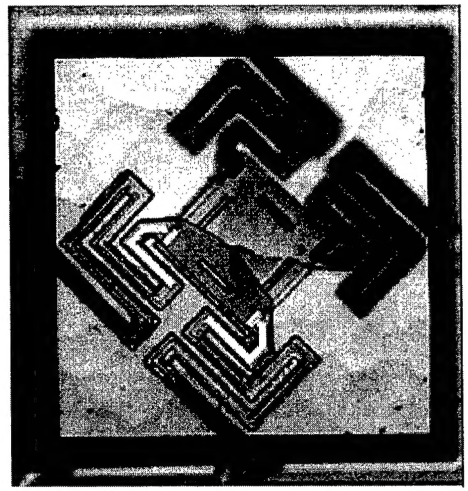


Figures 10-11 Microscope picture and particular of the device named *Accelerometer*. It is mainly made by a suspended plate anchored to the substrate by four sustaining arms. In this case two interdigitated capacitors series have been also added for driving and sensing motion in the device plane. They consist of a number of fingers which mesh with identical fingers connected to the suspended plate. For sensing purposes, when a device plane motion occurs, will change the finger overlap and thereby change the capacitance.

Once the RIE etching time has been optimized, several different damages have been induced to the structures, with the following TMAH etching, thus allowing to release correctly only two of the five designed devices. Some important damages were made to the exposed metals, as shown in the figures 12-17, and to the Passivation layer. In particular the anchoring points were the metals are encapsulated to the oxides are strongly stressed and damaged, so that a part of the structure named Susp_plate_3 collapse, as shown in figure 15. Some other different damages can be seen in the figures 12-18 for all the devices present in the die.



Figures 12-13 Microscope picture and a particular of the device named *Susp_plate_2*. After the etching procedures the segments of the designed springs are held together by the residual oxide and the TMAH etching has not worked correctly due to the residual oxide layer covering the holes.

Figures 14-15 Microscope pictures of the device named *Susp_plate_3*. Also in this case some different damages induced to the metals, the passivation layer and to the anchor points of the structure can be observed.

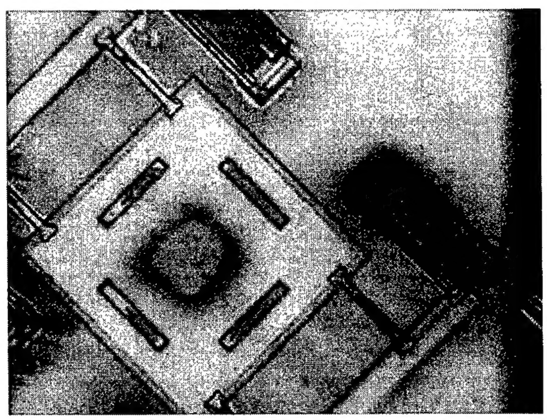
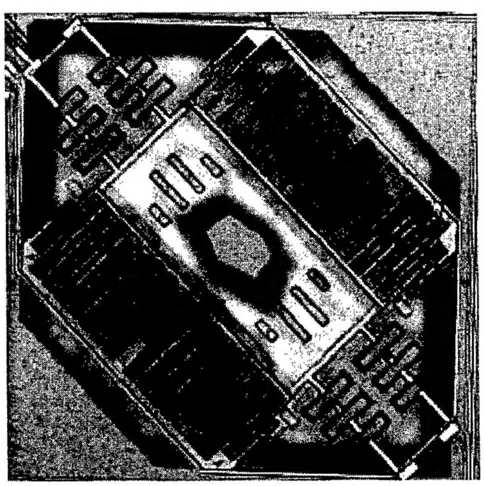
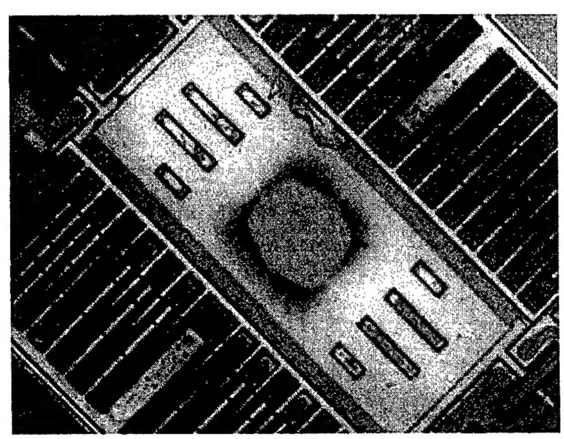


Figure 16 Microscope picture of the device named *Susp_plate_4.* The exposed metal layers have been damaged in this case thus reflecting a yellow light.

Figures 17-18 Microscope picture and particular of the device named *Accelerometer*. The damages to the meshing fingers does not allow in this case to use the electrostatic actuation and the residual oxide has not allowed to release correctly the structure.

After several different etching experiments two mechanical prototypes have been correctly released, as shown in figure 19 and in figure 20 for the devices named Susp_plate_2 and Accelerometer, respectively, even if the exposed metals are still damaged. By using a Wyko interferometric profiler some preliminary measures of the optical properties, the profile and the roughness of the above mentioned structures have been made at the laboratories of Redstone Arsenal, AL, USA. The residual stress during the TMAH induced a deformation of the suspended plate, as shown in figure 21 for the structure named Susp_plate_2. Moreover the profile and the value of the roughness of the surface should be acceptable in the central region of the plate and it will be verified by the optical experiments.

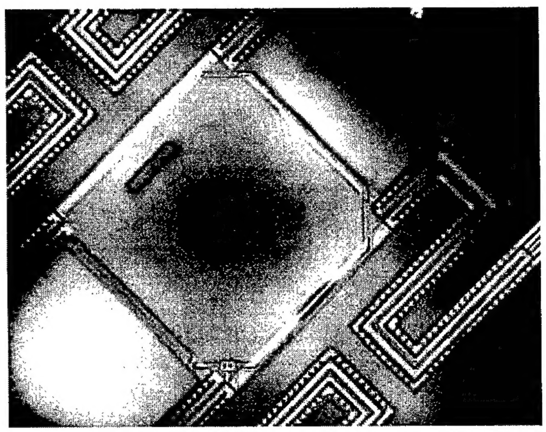


Figure 19 Microscope picture of the device named *Susp_plate_2*. It has been correctly released after a custom etching procedures that have been used at the laboratories of IBS (Ion Beam Service), Peynier, France. Some different etchant solutions, as HF have been used for about 10 seconds before the TMAH etching.

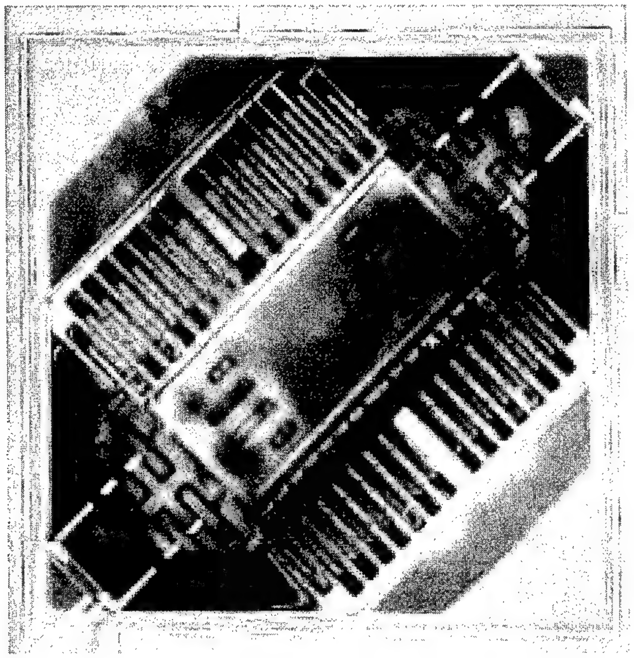


Figure 20 Microscope picture and of the device named *Accelerometer*. It has been correctly released after a custom etching procedure has been used at the laboratories of IBS (Ion Beam Service), Peynier, France. Some different etchant solutions, as HF have been used for about 10 seconds before the TMAH etching.

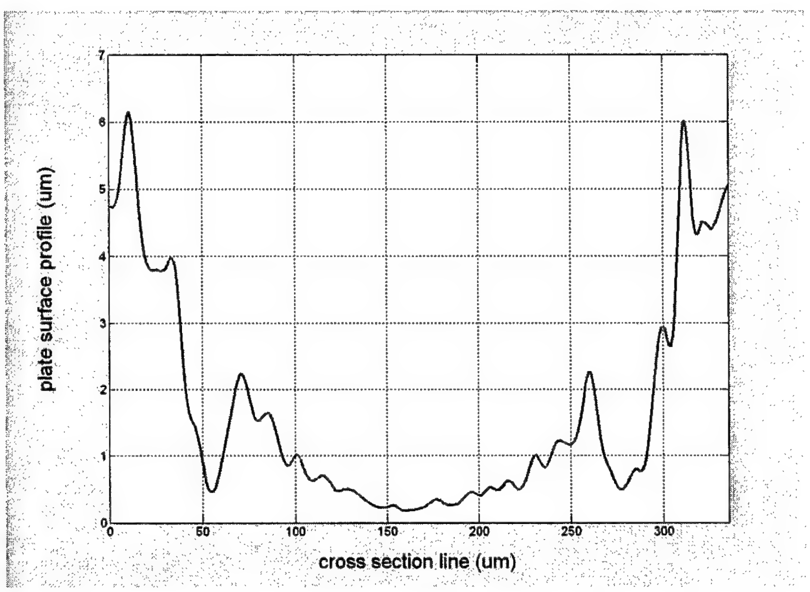


Figure 21 Profile of the structure named Susp_plate_2. Due to the residual stress during the etching procedures a deformation arise on the suspended plate probably at the end of the releasing process.

Some other simulations have been also made to design a suitable optical PBG structure to deposit over the realized devices. As an optimization parameter, the percentage of the transmitted and reflected incident light, has been considered as a function of the air gap variation. In this way the typical working mode of a transducer can be obtained for these devices. In fact, by considering the

reflected light at a fixed wavelength, for different values of the air gap between the micro-suspended plate and the fixed plate (made by glass and bonded to the die) a monotonic trend can be obtained for this optical output, as shown in figure 22. The sensitivity function of the conceived transducer can be better represented by the figure 23, thus showing a range for the air gap variation where good performances can be obtained for the proposed prototypes.

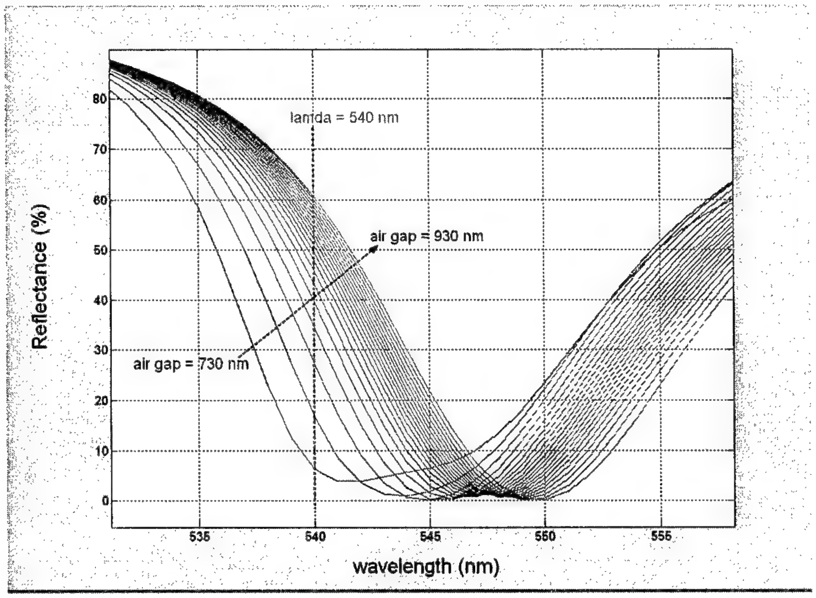


Figure 22 Reflectance variation of the proposed PBG structure, made by alternate layers of Ag and MgF_2, as a function of the wavelength and parameterized by the air gap variation. By fixing the wavelength of the incident beam a mechanical to optical transducer can be easily obtained.

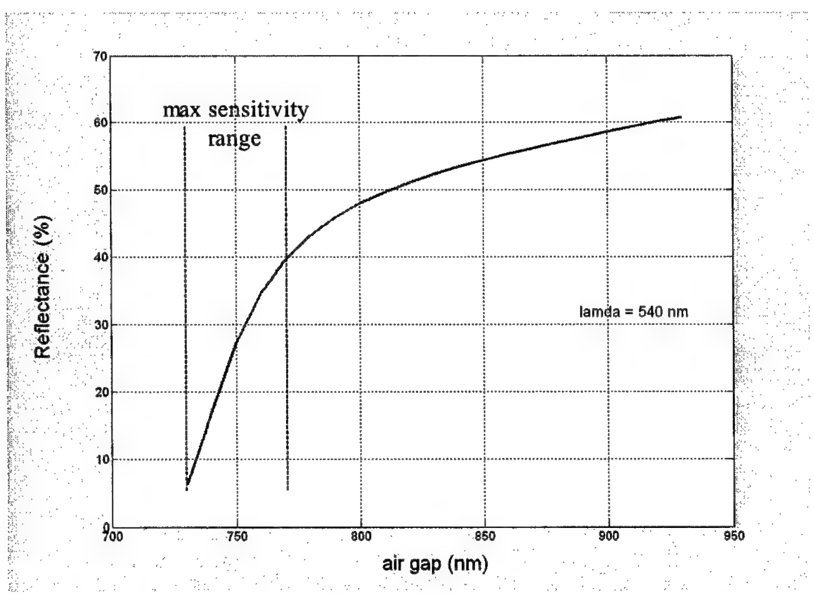


Figure 23 Sensitivity of the proposed optical device for an incident beam with a wavelength ?=540 nm, expressed as a function of the reflectance variation with respect to the air gap variation.

A new design was submitted to the same foundry, which is going to make free the new work for us. In fact, even if everybody knows that the standard CMOS technologies are not particularly suitable for the realization of these kind of devices, the errors present in the last dies were really unusual and unjustified, probably to some "shield effect" during the process.

In this last design some little modifications have been made to the previous structures and all the area of the submitted IC have been completely dedicated to these particular class of devices.

In fact, even if the structural integrity of the different structures has been compromised with the different etch phases, some improvements can be made to the structures which collapsed as first by making these modifications.

The layout of this last design is shown in figure 24 where one can observe that the Susp_plate1 and Susp_plate3 have been considerably changed. The mesas areas used as spacers, with respect to the bonded fixed plate, have been differently disposed and some other modifications have been made to the other structures.

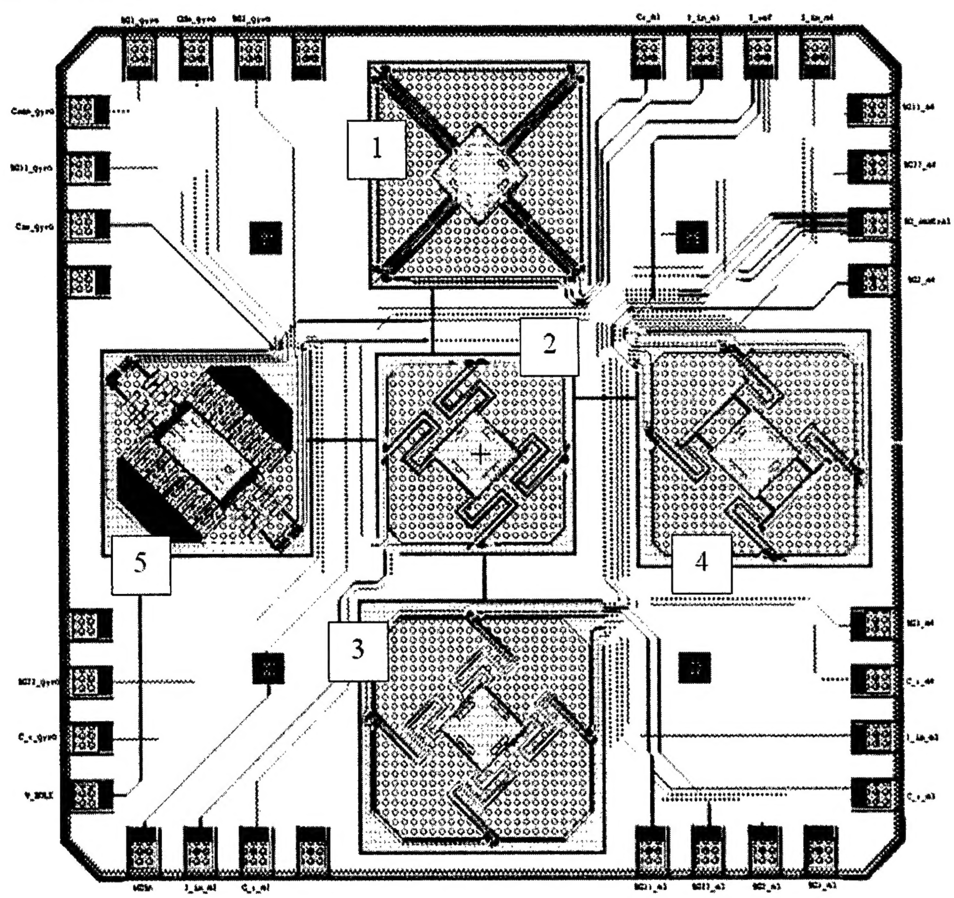


Figure 24 Layout of the last design. Five different devices are included in the same die, which has an area of 3x3 mm^2. A circular glass sample with a diameter of 2.5 nm has been bought and will be bonded or glued to the die after the etching and packaging procedures, thus allowing to perform the opto-electro-mechanical characterization of the conceived devices.

Conclusions

The developed activity dealt with the theoretical study, modelling and the development of Micro-Opto-Electro-Mechanical Systems (MOEMS) based on "Transparent Metals".

Some important results have been obtained regarding to the experimental macro-prototype, which has allowed to definitively confirm the encouraging theoretical results and performances of the proposed optical PBG structures. Different approaches to the problem has allowed to develop the mechanical models of the designed moving parts, by a lumped parameters hypothesis, the thermo-electro-mechanical models of the conceived thermal actuators, the electro-mechanical models of the conceived capacitive actuators/sensors and resistive (strain-gauge) sensors. After great efforts, the tuned finite element analysis and modelling, has allowed to improve the design of the generic device inside the last design, and to better evaluate the static and dynamic behaviours of the proposed actuators/sensors. The feasibility of a micro-prototype, realized by using a standard microelectronic process has been also verified together with the optimization of the TMAH etching procedures.

Therefore, each single subsystem of the proposed MOEMS has been studied, investigated, realized and characterized, then we are very close to the realization of a final prototype that will be completed, assembled and characterized in the next future.

During the development of the described activity several memories inherent to the topic, reported at the end of this report, have been published by the authors on National and International Conference Proceedings and International Journals. In the same period some people employed in the project earned some different advanced degree:

- Eng. *Nicolò Savalli*, pursued his Ph.D. degree on this topic and he is still writing his dissertation.
- Eng. *Luca Santonocito*, took his degree in Electronic Engineering.

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Scientific publications

National Conferences

1. N. Savalli, S. Baglio, M. Scalora, M. Bloemer, *Opto-Electro-Mechanical Systems based on Transparent Metals*, 2nd International Conference and 3rd general meeting of the European Society for Precision Engineering and Nanotechnology (EUSPEN), Vol. 1, may 27th –31th 2001, Turin, Italy.
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3. B. Andò, S. Baglio, S. Castorina, S. Graziani, N. Pitrone, N. Savalli, *Trasduttori foto-termo-meccanici ad alta efficienza basati su micro-lenti e tecnologie CMOS-compatibili,* GMEE atti del congresso Nazionale 2002, Parma.

International Conferences

4. S. Baglio, M. Bloemer, N. Savalli, M. Scalora, *Development of "active" PBG structures for realizing novel MOEMS based on "transparent metals"*, SPIE International Symposium on Smart Structures and Materials, Newport Beach, Vol. 4334-38, CA, USA, March 4-8 2001.
5. S. Baglio, S. Castorina, L. Fortuna, N. Savalli, *Technologies and Architectures For Autonomous Mems Microrobots,* ISCAS 2002, IEEE International Symposium on Circuits and Systems, Scottsdale, Arizona, USA, 26-29 May, 2002.
6. S. Baglio, S. Castorina, L. Fortuna, N. Savalli, *Development of Autonomous, Mobile Micro-Electro-Mechanical Devices*, ISCAS 2002, IEEE International Symposium on Circuits and Systems, Scottsdale, Arizona, USA, 26-29 May, 2002.
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10. S. Baglio, S. Castorina, L. Fortuna, N. Savalli, *Modeling and Design of Novel Photo-Thermo-Mechanical Microactuators,* Sensors & Actuators A, vol. 101, pp. 185-193, September, 2002.

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